BACK TO BASICS

Mr. Louis C. Lundstrom, Assistant Director of the GM Proving Ground, Milford, Michigan, wrote "Applied Basic Mechanics Solves a Civil Engineering Problem on Super-Elevated Curves of Proving Ground Test Track" for the January-February 1955 issue of the General Motors Engineering Journal. Extracts of his article are reproduced here with permission. They show how the fundamental concepts of mechanics can be applied to reduce a complex problem to manageable terms.

Written by Albert J. Nahas. Published with the support of the sponsors of the ASEE Stanford Engineering Case Program:

E. I. du Pont de Nemours and Company
The General Electric Foundation
IBM
Olin Corporation Charitable Trust
Union Carbide Corporation

APPLIED BASIC MECHANICS SOLVES A CIVIL ENGINEERING PROBLEM ON SUPER-ELEVATED CURVES OF PROVING GROUND TEST TRACK

by Louis C. Lundstrom
GM Proving Ground
Milford, Michigan

The 3.8 mile long test track at the General Motors Proving Ground with its two 77 per cent super-elevated curves was originally constructed of reinforced concrete. This construction lasted for over a quarter of a century; but, as in the case of all roads subjected to a heavy flow of traffic, resurfacing became necessary. The straight sections of the track presented no problem, but the curves did. Would it be possible to use conventional road paving machinery on the steep slopes or would specially designed machinery have to be used? What about the economics of the problem? These were a few of the questions that had to be answered. The solution to the problem was unique and now serves as a foundation upon which future resurfacing will be based.

The problem: *Resurface an unconventional roadway with conventional machinery.*

The General Motors Proving Ground at Milford, Michigan, is an outdoor laboratory where all types of automotive vehicles are scientifically tested and analyzed. On any average day, a total of 40,000 miles are driven over the more than 43.4 miles of every type of road surface imaginable contained in the 3,863 acres of the Proving Ground. In addition to the level roads, there are hills with grades ranging up to 60 per cent. Each hill and each level road aid in finding the answer to how automotive vehicles perform under all types of operating conditions.

There is also a test track at the Proving Ground which is five lanes wide, 3.8 miles long, and triangular in shape with curves at the three rounded corners. The upper lanes of two curves have a maximum slope of 77 per cent, providing an equilibrium speed of 85 miles per hour. Fig. 1 shows a view of the upper lane of one of the test track curves and gives an idea as to the extreme slope of the upper lane.

When this test track was constructed in 1926, reinforced concrete was used throughout. (A stiff mix of concrete is self-supporting, even on the 77 per cent slope.) As time went by, more traffic began to roll across the track and, as in normal highway use, one of the curves had to be reconditioned in 1935. Because the reinforced concrete provided good paving qualities, it was again used on the curve. Although it was used successfully it had two drawbacks: (a) it was necessary to completely

close the track to all traffic for many months and (b) the large amount of hand labor made the job relatively costly. Closing of the test track seriously handicaps Proving Ground operations, as most testing schedules require some high speed operation.

The extreme degree of the sloped curves presented a problem during winter operation when conventional snowplow equipment proved useless. In an effort to clear away the snow and ice from the upper lanes, the use of large amounts of ice and snow melting chemicals became necessary. As a result, deterioration of the original concrete surface began to take place. This deterioration was accelerated during World War II when the track was used for testing heavy tanks and other combat vehicles for military purposes. The testing of military vehicles, coupled with the use of large amounts of snow and ice melting chemicals, made necessary resurfacing of the entire track. Settlement of entire slabs had, in a few cases, produced large bumps that made driving difficult.

When resurfacing of the track was undertaken in 1945, it was decided that bituminous concrete would be used as the resurfacing material. This material, composed of a densely graded aggregate and a binder of asphalt cement, has a high coefficient of friction and is capable of carrying heavy loads. The use of bituminous concrete was, therefore, ideally suited for test track purposes.

Conventional road paving machinery was used to apply bituminous concrete to the straight sections of the track and to the nearly level inside lanes of the super-elevated curves. This machinery, however, would not work on the steeply banked outside lanes of the curves. In an effort to resurface the curves, simple wooden strike-off boxes were made. After much effort, a hot bituminous mixture was spread over the upper lanes and then cross-rolled by winching a conventional pavement roller up and down the steep slopes. The resulting surface, however, was too rough for high speed operation and it became necessary to remove the bituminous mat -- once again leaving the original weathered reinforced concrete surface on the upper lanes of the curves.

The original reinforced concrete surface which had provided a satisfactory road for over a quarter of a century had been subjected to conditions not usually encountered on an average highway. By 1952, the condition of the curves made resurfacing imperative.

It was realized from the start that resurfacing the curves with a bituminous concrete would be a difficult job. The experience gained from the attempt at resurfacing the curves in 1945 showed that, if a satisfactory surface was to be attained, a paving machine must be used to spread the bituminous mixture and that another method must be found for compacting the surface with a pavement roller -- different from the method of winching the roller up and down the slopes. With the economics of the problem in mind, it was evident that special machinery was impractical. Conventional road paving machinery might be used if certain modifications were made to allow for satisfactory operation on the steep slopes and if a way could be found to properly support the machines when in operation. Through the application of basic mechanics, a solution was found to these problems.

Method of Support

Successful operation of bituminous paving and rolling machinery on the side slopes required special mobile supports. A truck and a tractor were selected as the mobile supports and these were operated on a 10 ft. wide dirt roadway specially built around the top rim of the curves. To properly guide these vehicles and to absorb the large reactions, a special reinforced curbing, 1 ft. wide by 3 ft. deep, was placed against the top edge of the original concrete pavement slabs. The curbing,placed 2 ft. into the ground, now serves as support for the guard-rail posts.

Both the tractor and truck were cable-connected to the machines they supported; but, in both cases, a complete analysis was required in order to design the necessary cable-supporting mechanisms.

Support of the Tamping-Leveling Paving Machine

One of the reasons for choosing the track-laying tractor for support was its slow-speed operation which allowed it to inch along at the same speed as the paving machine.

. . .

A line from the tractor winch was routed laterally through the tractor to a block and tackle system which connected the tractor and the paving machine. Conventional block and tackle rigging was first tried, with the lower sheave fastened to the only available attachment near the center of the paving machine. During initial tests, it was found that the front of the loaded paving machine was too heavy and would drift down-slope; that is, the center of gravity was ahead of the support cables. As it was impractical to move the main attachment, the anchor end

of the block and tackle was moved to the front of the tractor and one line was passed through an additional snatch block attached to the high-front corner of the paving machine. This forward cable produced a turning couple to balance the couple produced by the forward location of the paving machine's center of gravity.

The added side pull on the front of the tractor required the installation of a horizontal guide wheel to support and guide the tractor along the curbing. In addition, a special calibrated spring was used at the anchor end of the cable to indicate the actual amount of side pull. The tractor operator therefore, adjusted the winch to carry just the right amount of support for the paving machine.

Support of the Three-Axle Tandem Pavement Roller

The three-axle tandem pavement roller was supported on the steep slope of the curves by a cable which was connected to a winch positioned on the flat bed of the supporting truck. Fig. 1 shows a view of the pavement roller and supporting truck in operation. . . .

Side forces on the supporting truck were absorbed by two horizontal and two vertical truck tires which were free to roll along the special curbing. The four support tires were mounted on a heavy cross-frame that was pivoted along the right side of the truck frame. The floating action of this framework allowed the truck to operate on the irregular dirt roadway without seriously affecting the position of the four support tires. Two tons of weight placed on the far side of the support-wheel frame approximately balanced the couple produced by the cable pull and left the truck lightly loaded.

. . . .

To eliminate all shoving and grooving of the fresh bituminous mix, the road reaction on the roller had to be normal to the road surface and equally distributed across the roller face. In Fig.1a it can be seen that there were only three forces which acted on the roller -- the force of gravity W acting through the center of gravity, the normal reaction N, and the cable pull F. As the line of action of the force W and the line of action of the desired normal reaction N intersected at the center of gravity of the machine, equilibrium could only be obtained by having force F also pass through the center of gravity. This was accomplished by using a special hydraulically controlled hitch mounted on the side of the roller. The hitch permitted both longitudinal and vertical adjustment as required by the roller's operation on the upper and lower lanes. (Fig. 2)

Fig. 1

Pavement Roller in Top Lane

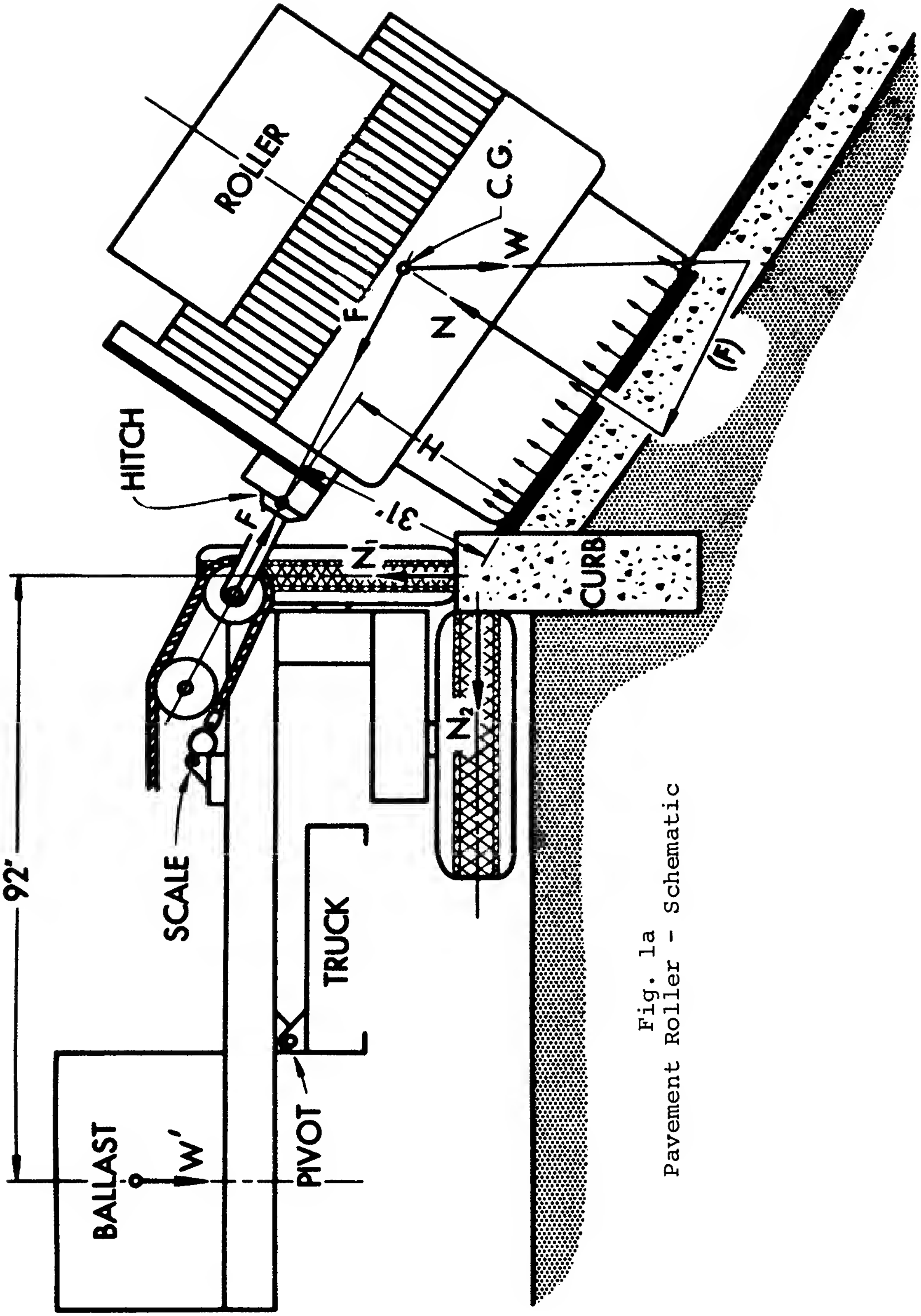
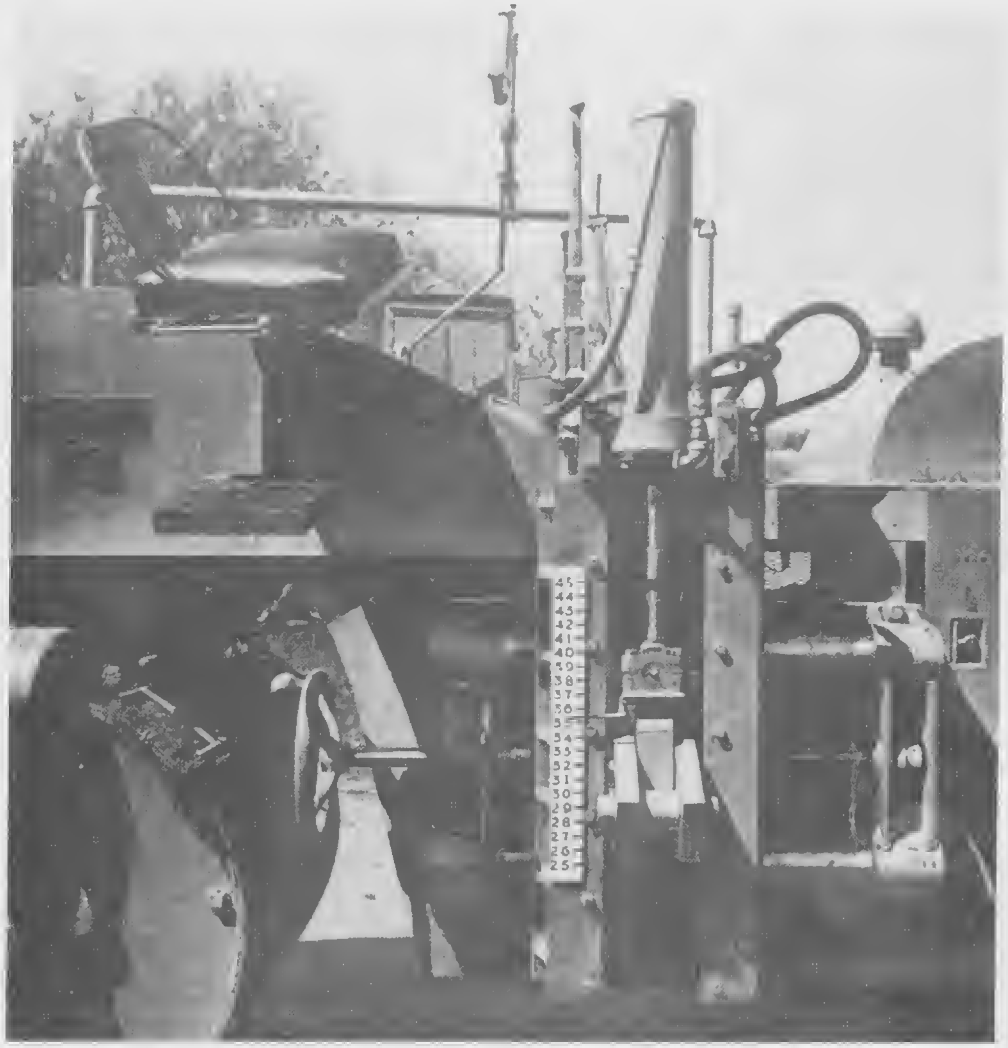


Fig. 1a
Pavement Roller - Schematic



A special hydraulically controlled hitch was mounted on the side of the modified pavement roller to assure that the force of the cable pull would continually pass through the center of gravity of the roller, a condition which was necessary to assure that uniform compaction of the bituminous concrete resulted. The scale on the roller was calibrated to indicate to the operator the height to which the hitch had to be raised or lowered, as the distance of the roller from the curb varied. A hand wheel for manually adjusting the fore-and-aft position of the hydraulic hitch also was provided as the location of the roller's center of gravity depended upon the amount and location of ballast on the roller.

Fig. 2

Cable Hitch Adjustment

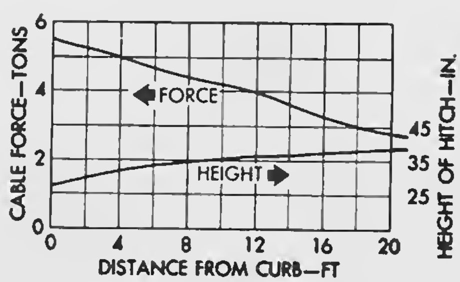


Fig. 2a

To aid in maintaining a constant balance of forces necessary to assure uniform compaction of the bituminous concrete, a force analysis was made and the results plotted, which determined the required height of the hydraulic hitch with change in cable force as the distance of the roller from the curb varied.

Due to the parabolic cross section of the track, direct calculations of the forces on the roller would have been very complicated; therefore, the problem was solved graphically. Fig. 1a shows the very simple triangle of forces involved in the graphical solution necessary to find the required height H of the hitch and the roller cable force F as the distance of the roller from the curb varied. . . .

Modification of Tamping-Leveling Paving Machine

The major requirements that had to be fulfilled by the paving machine, which spread the hot bituminous mixture to the desired depth and then compacted it with a set of tamper bars, were to provide a negative crown and a curved surface finish which would closely match that of the original parabolic cross section of the upper lanes. This meant that the bottom of the machine had to be curved.

. . . .

In order to control the flow of material through the machine from the forward hopper to the rear strike-off plates while it operated on the steep slopes, wedge plates and baffles were used in conjunction with the standard machine's conveyors and lateral spreader screws to keep the material from falling to the low side.

Modification of the Three-Axle Tandem Pavement Roller

A three-axle tandem pavement roller was selected for the rolling operation because it effectively leveled out any irregularities left by the paving machine. Modifications of the roller started with the use of special rollers machined to a radius of curvature of 60 ft. Thus, in the high speed lane, the most ideal condition was obtained. Fortunately, the compaction and operation of these special rollers on surfaces of smaller radii of curvature was very satisfactory.

. . . .

Adjustment of the rollers was required so that all three rollers would simultaneously be in contact with the surface of the saucer-shaped track. In effect, the center roller was 1/4 in. lower than the end rollers.

The fore-and-aft position of the cable support hitch was manually adjustable so that the driver could balance the machine for the proper "feel." When compacting material adjacent to the curb, the drivers usually preferred to operate slightly off balance to the rear so that the guide (rear) roller would

be several inches lower on the slope than the lead or drive roller. This enabled the drive roller to compact loosely spread material adjacent to the curb and eliminated all hand tamping.

The three-axle tandem roller was rated at 10 tons metal weight and 15 tons ballasted. To ease the load on the support cable as much as possible, the roller was used at approximately 11 tons and compaction was very satisfactory.

Delivery of the Bituminous Concrete to the Paving Machine

The hot bituminous concrete mix used for resurfacing was prepared at a mixing plant and delivered to the job site in dump trucks. Delivery of the mixture from the dump trucks to the paving machine presented a difficult problem.

Conveyors from the lower inside lanes of the track would have been too long and difficult to maneuver. It was decided, therefore, to attach a belt conveyor and hopper to the front of the support tractor. Hot bituminous mix, delivered to the site in trucks, was dumped into the hopper and then carried on a 14 ft. belt across the curbing to the hopper of the paving machine. The conveyor was not operated continuously as it was desirable to move the material in batches to retain as much heat as possible. The conveyor's capacity of 120 tons per hour was not used continuously.

As the roadway behind the curbing was very narrow, the dump trucks could not turn around in the vicinity of the paving operations. This required backing the dump trucks as much as 2,400 ft. Fortunately, the back-up distance was the greatest to the transitions of the super-elevated curves, where paving operations were necessarily slow. As the supply distance decreased, normal speed of paving could be maintained.

Summary

The resurfacing of the three super-elevated curves was a project that presented problems which were largely solved by the application of engineering fundamentals. The solutions generally were not difficult when reduced to single problems. The experience and knowledge gained will be applied when similar resurfacing again becomes necessary in the future.

The success of this paving operation has also demonstrated to bituminous engineers the feasibility of applying bituminous linings to steep dam facings and canal linings by the use of paving machines. The same precision of form and rolling operation specified for the roadway would not be required but the methods of application could be the same.

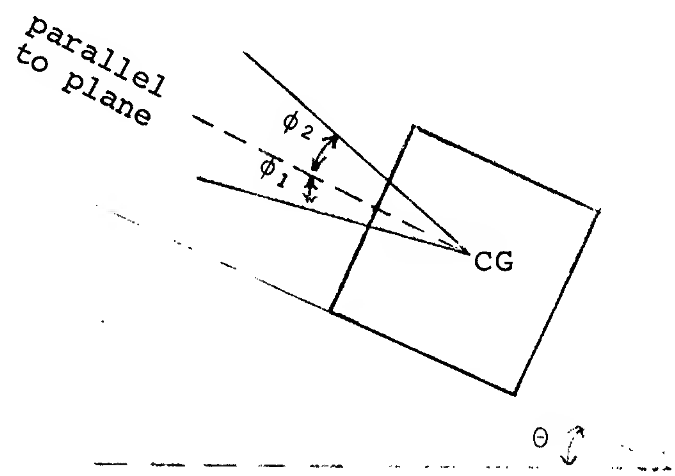
SUGGESTED QUESTIONS:

1. As the roller moves in the top two lanes of the test track, the angle formed between the road surface and the horizontal plane varies from 29.7° to 13.4°. What force, parallel to the plane of the pavement, must be applied to keep the roller from sliding down hill in either position without relying on friction forces? Use an operating weight of 11 tons.

2. The cable from the roller support truck is attached to a movable hitch on the roller. The operator adjusts the hitch so that the line of action of the cable force always passes through the CG of the roller. The angles between the cable and a line parallel to the pavement are shown in the schematic below. What force should be applied to the cable in each case so that no friction force is generated between the pavement and the roller? What is the normal force between pavement and roller in each case?

top lane
$\phi_1 = 8°$

second lane
$\phi_2 = 8.5°$



3. Why is it desirable that the line of action of the cable force pass through the CG? Explain quantitatively what would happen if the line of action passed x inches above the CG.

4. Using the cable force found in question 2, determine the largest ballast weight that should be placed on the support truck platform. The platform is attached to the truck only at the pivot pin. For steady operation on the rough dirt service roadway no force should be transmitted between the truck and the platform through the pivot pin. See Figure 1a.

INSTRUCTOR'S NOTES

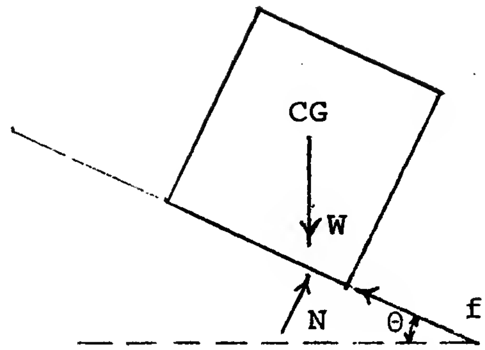
1. Using similar triangles or trigonometry,

$f = W \sin \Theta$

Top lane:

$\Theta = 29.7°$; $f = (22{,}000)(.495)$

$= \underline{\underline{10{,}890 \text{ lb}}}$



Second lane:

$\Theta = 13.4°$; $f = (22{,}000)(.232)$

$= \underline{\underline{5{,}100 \text{ lb}}}$

2. a. The parallel component of the cable force, F, must equal the friction force. Then

$$f = F \cos \phi$$

Top lane: $F = \dfrac{10{,}890}{\cos 8°} = \underline{\underline{11{,}000 \text{ lb}}}$

Second lane:

$$F = \frac{5100}{\cos 8.5°} = \underline{\underline{5{,}160 \text{ lb}}}$$

(For all practical purposes 11,000 = 10,890 and 5160 = 5100 i.e., The cosine of a small angle may here be assumed = 1)

b. $N = W \cos \Theta \pm F \sin \phi$

Top lane: $N = (22{,}000) \cos(29.7) + (11{,}000) \sin(8)$
$= 19{,}100 + 1{,}530$
$= \underline{\underline{20{,}630 \text{ lb}}}$

Second lane: $N = (22{,}000) \cos(13.4) - (5{,}160) \sin(8.5)$
$= 21{,}410 - 764$
$= \underline{\underline{20{,}646 \text{ lb}}}$

Note that despite the variation in geometry the force exerted by the roller in compacting the asphalt is not greatly affected.

3. Any force acting on the body which does not pass through the center of gravity will cause a moment which must be balanced by another force. The weight must go through the center of gravity. Therefore, the normal force must shift toward the uphill side of the roller by some distance, y.

$$\circlearrowleft + \quad \Sigma M_{CG} = 0$$

$$(\text{cable force})(x) - N(y) = 0$$

$$y = \frac{11{,}000}{20{,}630}(x) = .532x \text{ (for top lane)}$$

This shift in the force distribution on the roller would cause uneven compaction of the concrete.

4. Set force in pivot pin equal to zero. Sum moments about intersection of N_1 and N_2.

$$\circlearrowright + \quad \Sigma M = 0$$

$$F(31) - W(92) = 0$$

$$W = \frac{(11{,}000)(31)}{92}$$

$$= \underline{\underline{3720 \text{ lb}}}$$

For the actual operation 2 tons (4000 lbs) of ballast was used.